Particle Trajectory Analysis for High Ice Water Content (HIWC) Flight Requirements

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NASA Glenn Research Center
Icing Branch

Task & Objectives

- Task description:
  - Analyze ice particle and supercooled liquid particle trajectories on an airframe geometry suitable for the High Ice Water Content flight campaign
- Objectives:
  - Identify regions / locations suitable for cloud physics and other instruments to be mounted for
    - Certain cloud physics probes need to be in flow and particle concentrations similar to free stream
      - Need to avoid shadow zones (locations where particles are absent)
      - Need to avoid high concentration zones (due to particle bounce)
  - Identify if supercooled liquid particles can impinge on proposed cloud profiling radar radome on top of fuselage
    - Ice build up at this location could pose FOD hazard

Approach

- Approach description:
  - Develop viscous flow solution for a 3D representative business jet geometry flying at the conditions specified
  - Utilize LEWICE3D to predict 100 μm particle trajectories to define off-body concentrations for two cases:
    - Impinge (no bounce)
      - This case defines where concentrations if no bouncing (unrealistic in glaciated conditions)
    - Impinge and bounce (no loss or break up)
      - This case defines the outer edge boundary for instrument location if particles were fully elastic and did not break up (also unrealistic)
    - Actual particle concentrations will vary within these two boundaries because there will be particle bounce, but also breakup and energy loss
  - Utilize LEWICE3D to predict 20 μm particle trajectories to define off-body concentrations for top fuselage radome

Background

- Lewice3D
  - Grid based 3D ice accretion code developed by the Icing Branch at Glenn Research Center.
  - User supplies grid based flow solution. Solution can be structured, unstructured or panel code based.
  - Trajectories are calculated using predictor-corrector method developed by Hillyer Norment.
  - Collection Efficiencies for complex regions calculated using Monte-Carlo Method developed by Bidwell
  - Streamlines are calculating using 4th Order Runge-Kutta Scheme.
  - Ice Growth along streamlines calculated using modified LEWICE 2D scheme.

Background

- Lewice3D Unstructured Grid Interface
  - Interface allows use of Euler or Navier-Stokes unstructured grid based flows in Lewice3D.
  - User inputs grid, flow solution and surface model into 3 separate files.
  - Interface has been used with Fluent, USM3D, and Rampant flow solutions.

Background

- USM3D Flow Solver
  - Tetrahedral cell-centered, finite volume, Euler and Navier-Stokes solver
  - Time Integration: Implicit Point GS & Explicit RK
    - Local time stepping & Residual smoothing for convergence acceleration
  - Upwind flux functions
    - Roe's Flux Difference Splitting
    - Van Leer's Flux Vector Splitting (Untested)
  - Superbee and MinMod flux limiters
  - Spalart-Allmaras turbulence model with Wall function
  - Computer Platforms: Cray, Sun, SGI
  - Multitasking: Efficiency of 6 out of 10 processors on Cray
  - Dynamic Memory – eliminates need to recompile

Conditions For Analyses

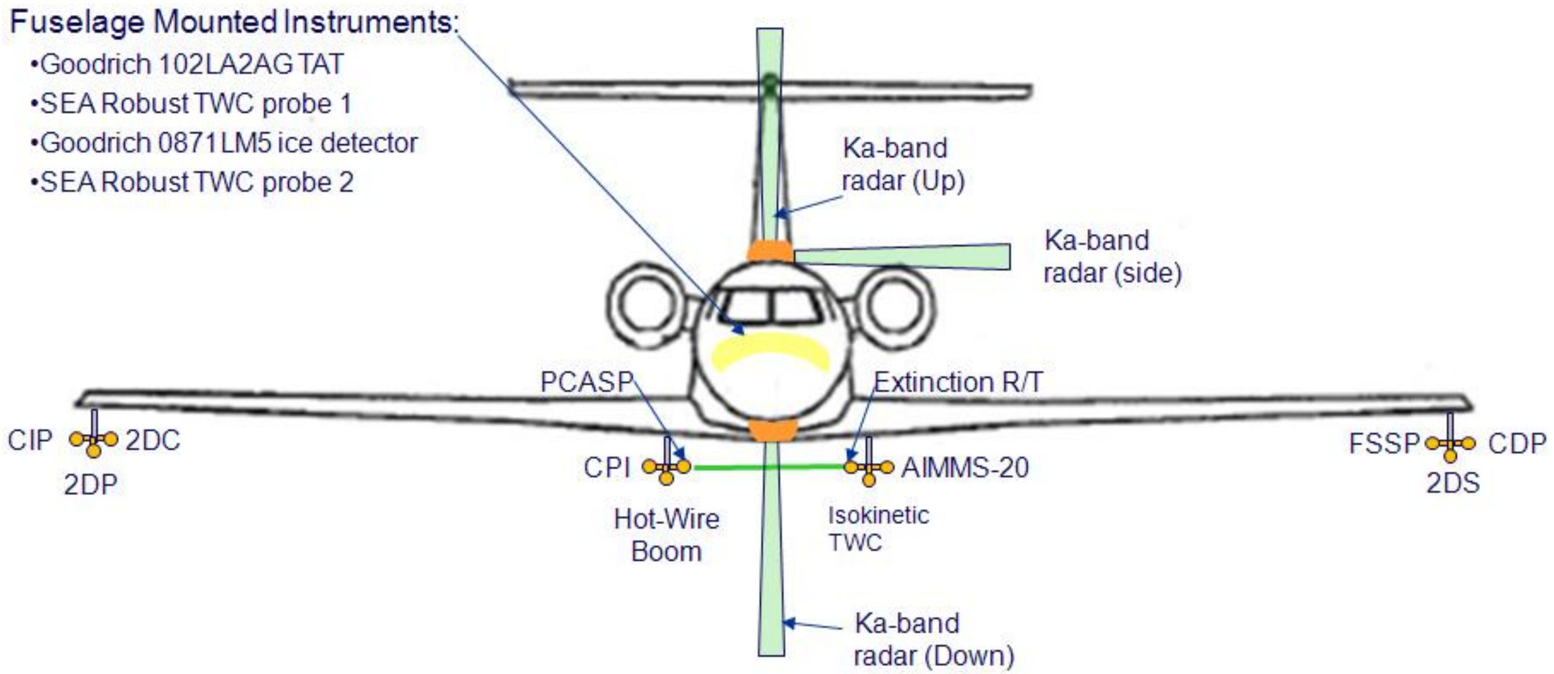
- Conditions for Viscous Flow Solver
  - Mach Number, 0.74
  - Reynolds Number, 15.5 Million
  - Aircraft Angle-of-Attack; 5^{o}
  - Tropical Day Altitude, 40,000 ft
  - Static Temperature, 231 K, (-41C)
  - Static Pressure, 18754 pascals (2.72 psi)
- Conditions for Particle Trajectory Analysis
  - Particle sizes; 20, 100 mm
  - No Loss or Breakup for Bouncing Model
    - Coefficient of Restitution=1.0
    - Coefficient of Dynamic Friction=0.0
  - Tropical Day Altitude: 40,000 ft
  - True Airspeed: 225 m/s, (438 knots)
  - Static Pressure: 18,754 pascals (2.72 psi)
  - Static Temperature, 231 K (-41C)

Computational Performance

- VGRID half-plane model Inviscid Euler grid contained 2,402,534 nodes and 14,017,309 tetrahedron.
- USM3D Viscous half-plane model flow solutions required 5 hours on 192 processors of a Linux Cluster for 15000 iterations.
- The Log(Residuals) after 15000 iterations for the half-plane model solutions were approximately -3.8.
- The Lewice3D Monte-Carlo based collection efficiency calculations required an average of 12 hours of CPU time per particle size (~4 Million particle trajectories) on a multiprocessor Linux workstation.

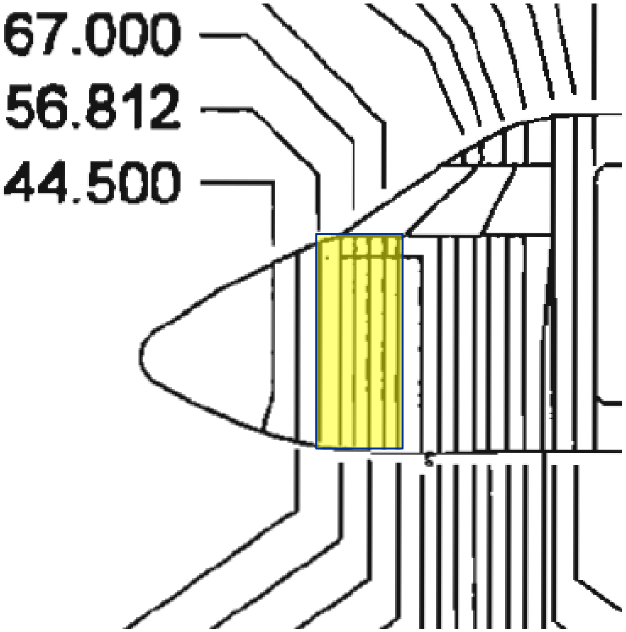
Aircraft Geometry and Concept of Instrument Layout

- This concept for instrument locations defines specific locations for the particle trajectory analysis
  - Fuselage mounted instruments (high resolution grids near surface)
  - Inboard, under wing pylons
  - Wing tip, under wing pylons
  - Upper fuselage, radome (for supercooled liquid)



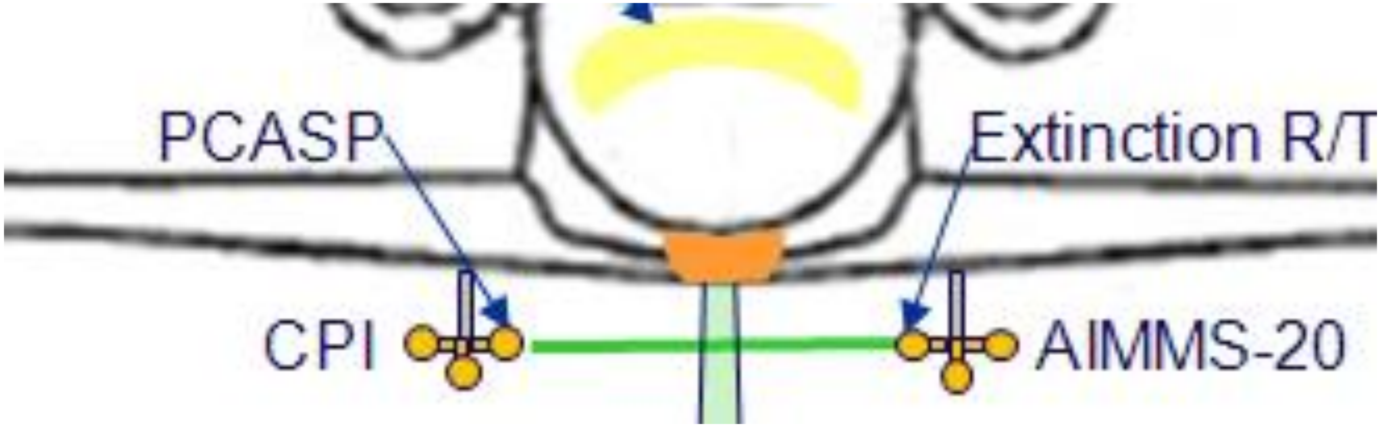
Locations for Particle Concentration Contours

- Fuselage mounted instruments
  - Four small probes that mount directly to fuselage skin near the nose (approx 4 inches in height)
  - Desired approximate station location = 57” (near plane with pitots)
  - Alternate station location on access panel (station 80”)
- Particle concentration with and without particle bounce



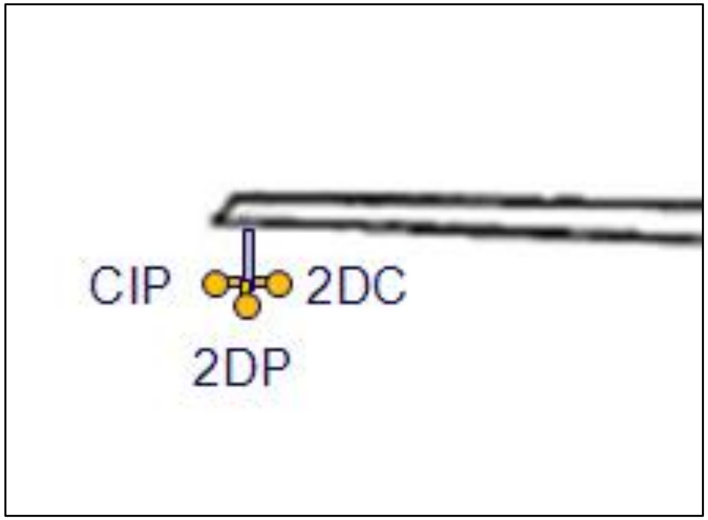
Locations for Particle Concentration Contours

- Inboard wing pylon mounted instruments
  - Approximate location of instruments will be:
    - Station: 270”
    - Waterline: +30”
    - Butt Line: 51” +- 12”
  - Concentration analysis at station 270 with a box from WL 0 to 100 and Butt line -100 to +100
  - Particle concentration with and without particle bounce

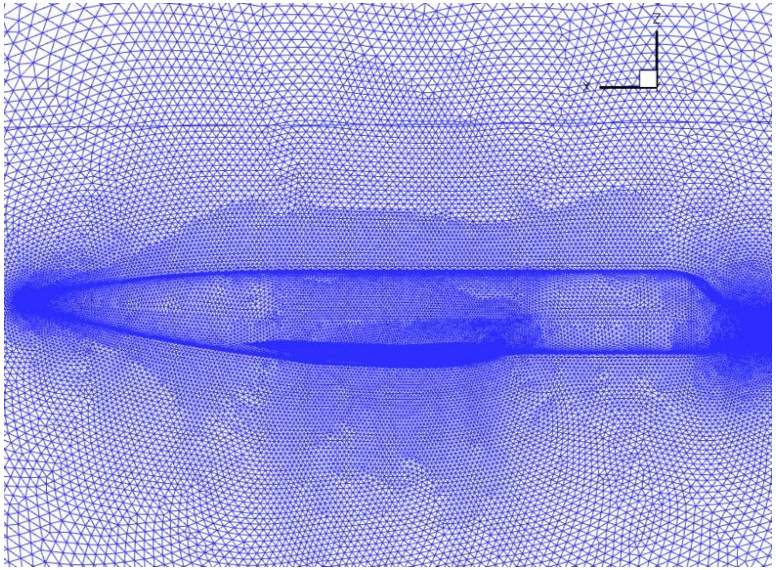


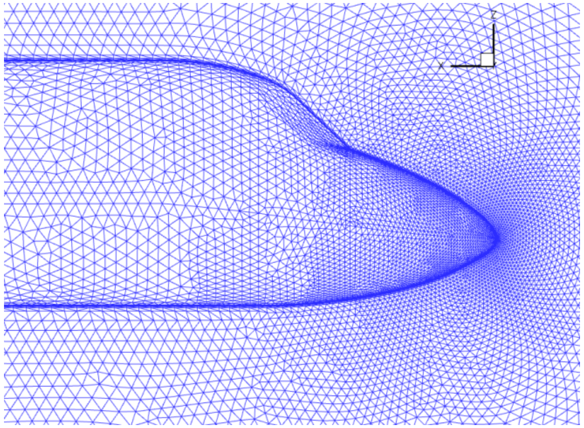
Locations for Particle Concentration Contours

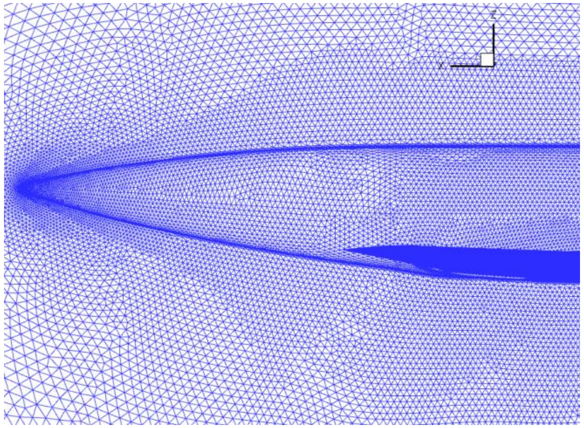
- Wing-tip pylon mounted instruments
  - Approximate location of instruments will be:
    - Station: 512”
    - Waterline: +30”
    - Butt Line: +-400” +- 12”
  - Concentration analysis at station 512 with a box from WL 0 to 100 and Butt line 350 to 450
  - Particle concentration with and without particle bounce



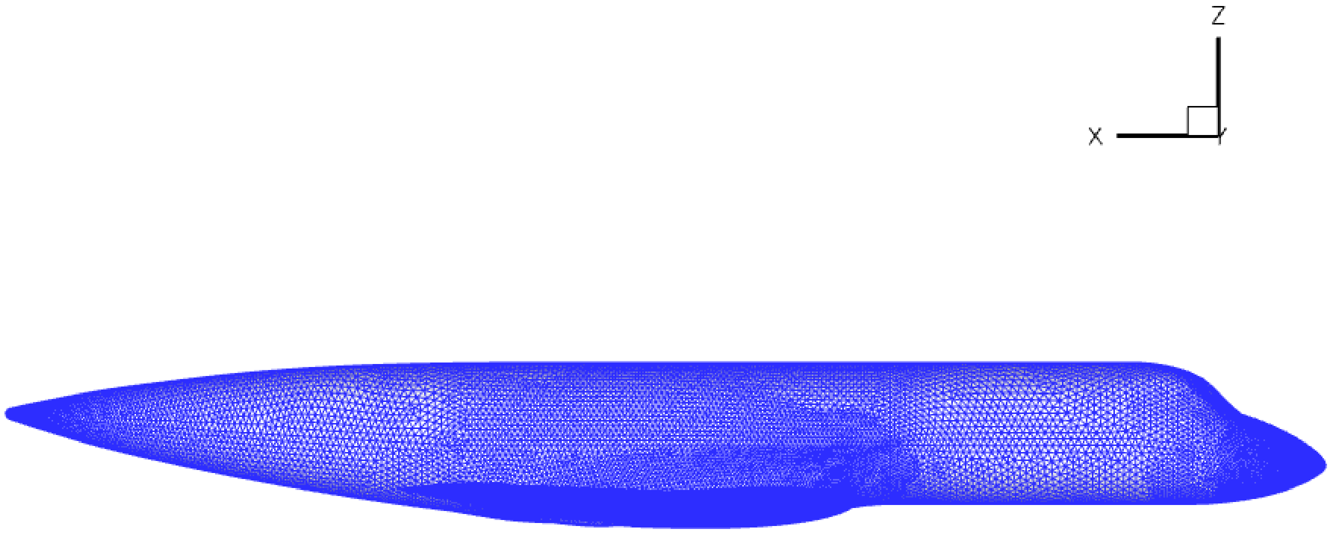
VGRID Volume Grid for Fuselage



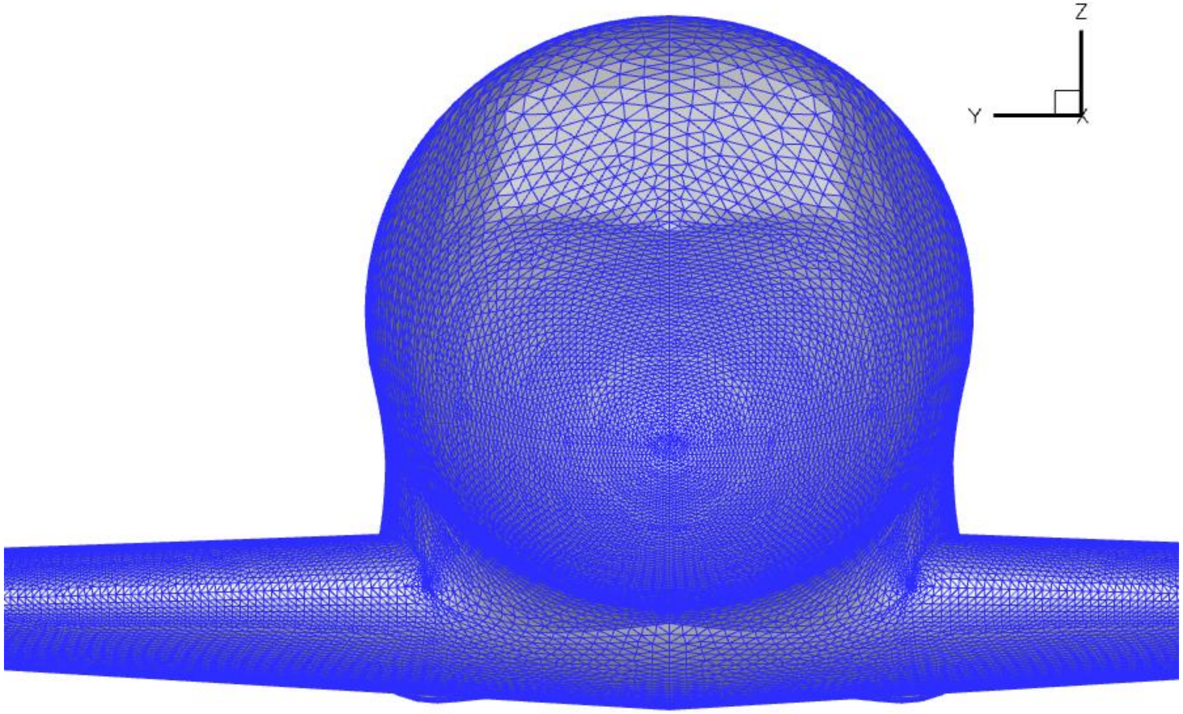




VGRID Surface Grid for Flow Model



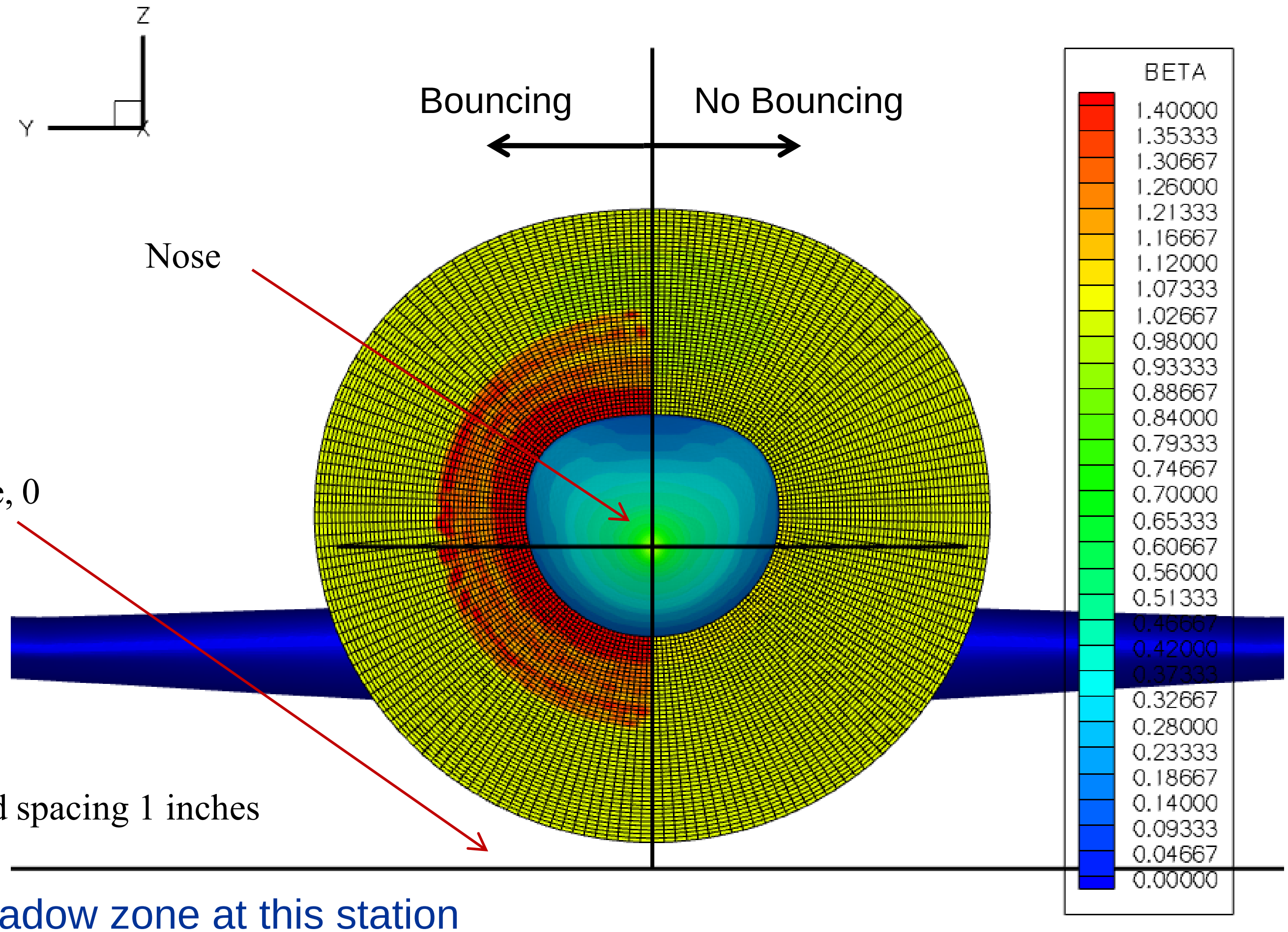
VGRID Surface Grid for Flow Model



Particle Concentration Contours for Fuselage Mounted Instruments

Tropical Day; AOAA, 5°; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Axial Station, 57 inches

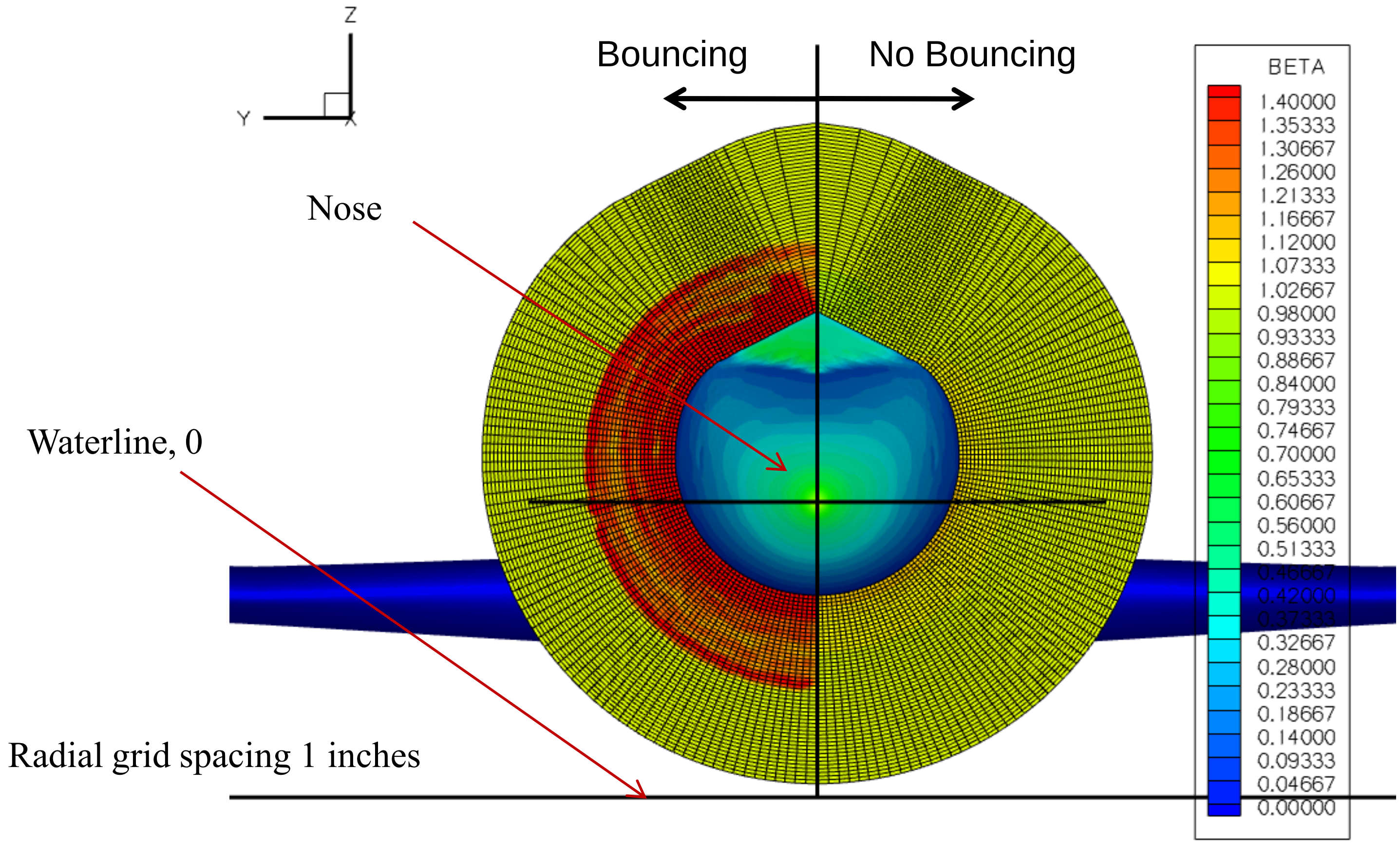


- No shadow zone at this station
- Approximate off-body distance to free stream = 21 inches; consistent about radial position

Particle Concentration Contours for Fuselage Mounted Instruments

Tropical Day; AOAA, 5°; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Axial Station, 80 inches

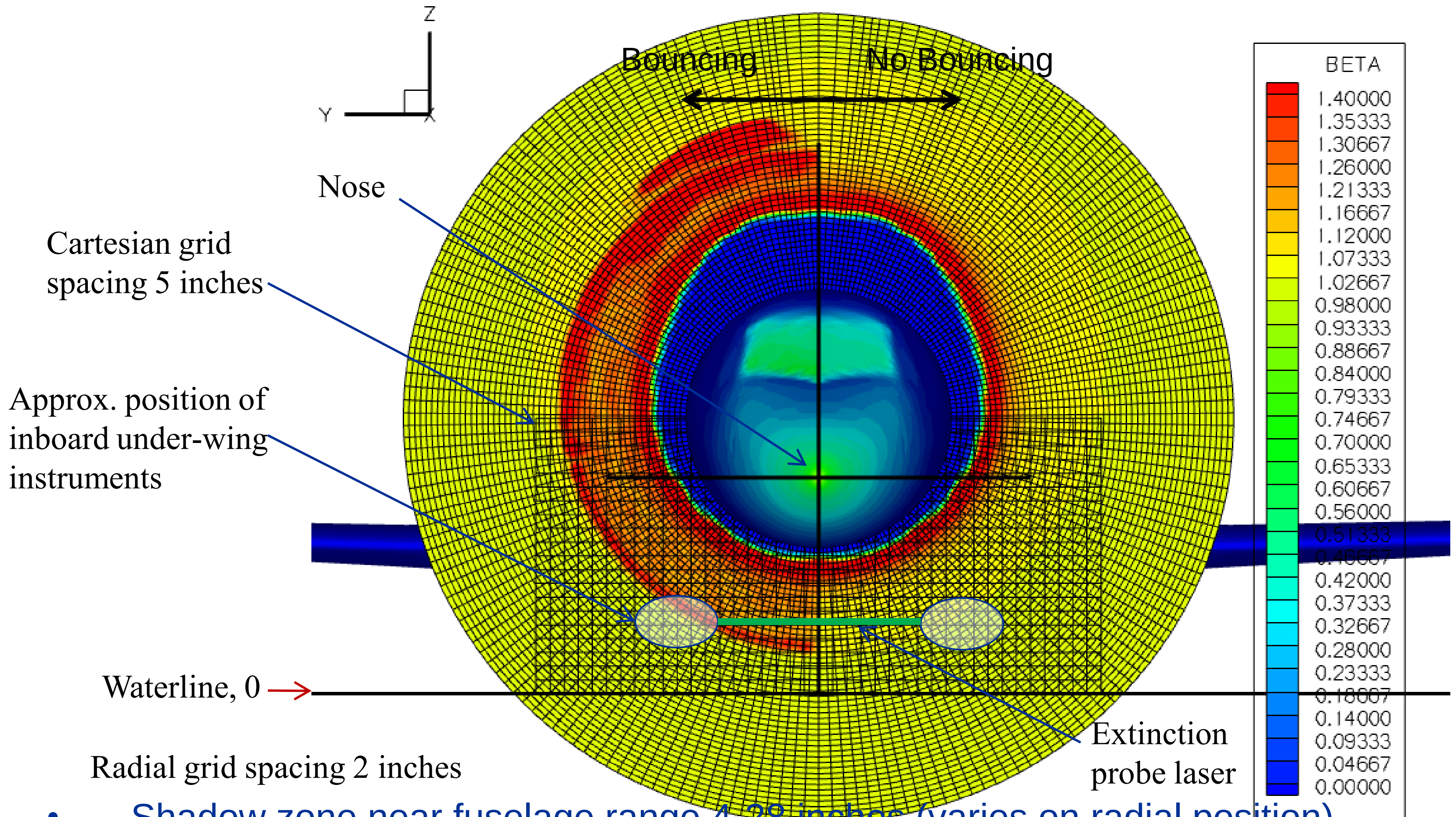


- No shadow zone at this station
- Approximate off-body distance to free stream = 23 inches; consistent about radial position

Particle Concentration Contours for Inboard, under-wing mounted instruments

Tropical Day; AOAA, 5º; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Axial Station, 270 inches

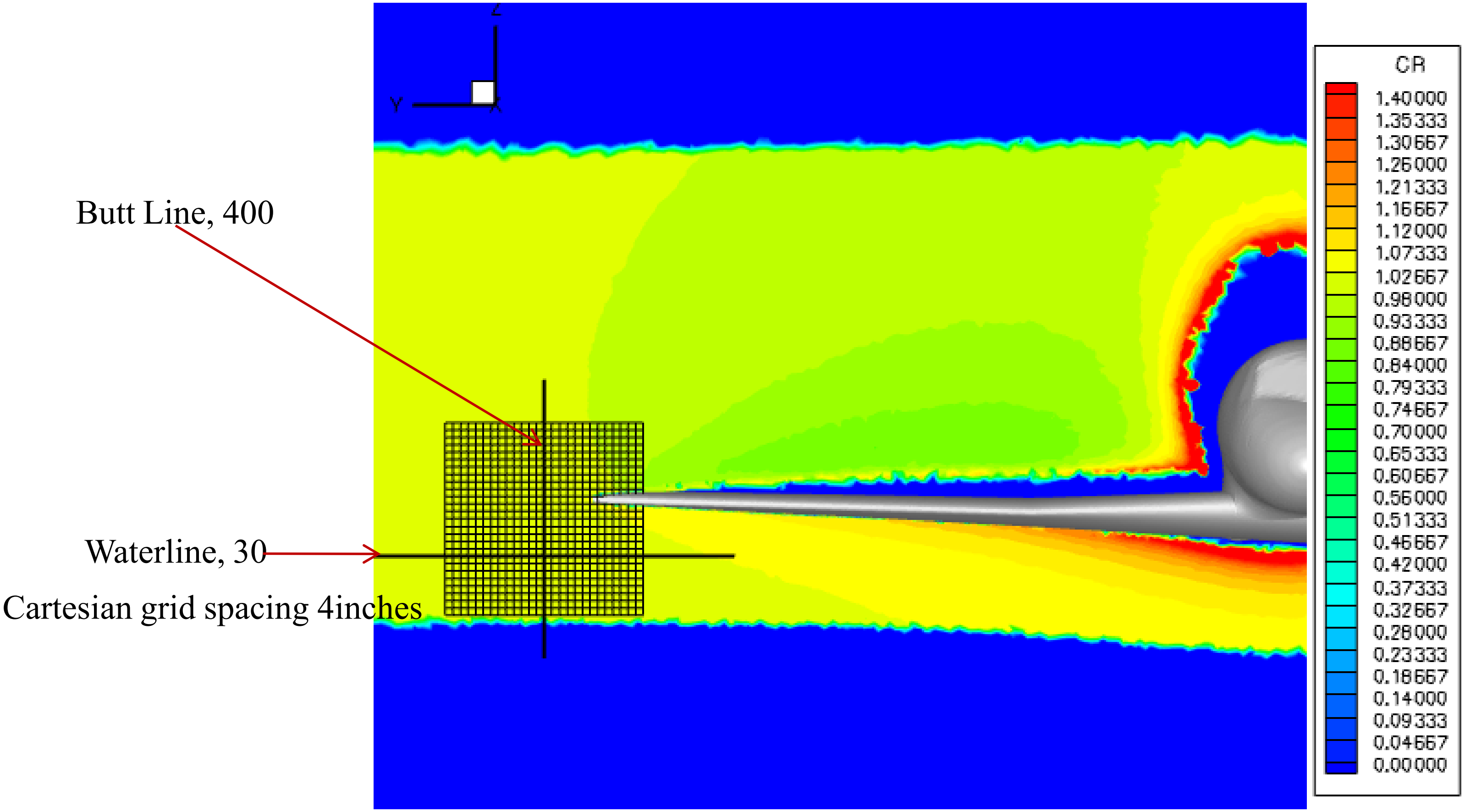


- Shadow zone near fuselage range 4-28 inches (varies on radial position)
- Inboard instrument location on outer edge of off-body high concentration due to particle bounce from fuselage (38 inch)

Particle Concentration Ratio Contours for wing tip mounted instruments

Tropical Day; AOAA, 5°; M, .74; Altitude, 40000 ft

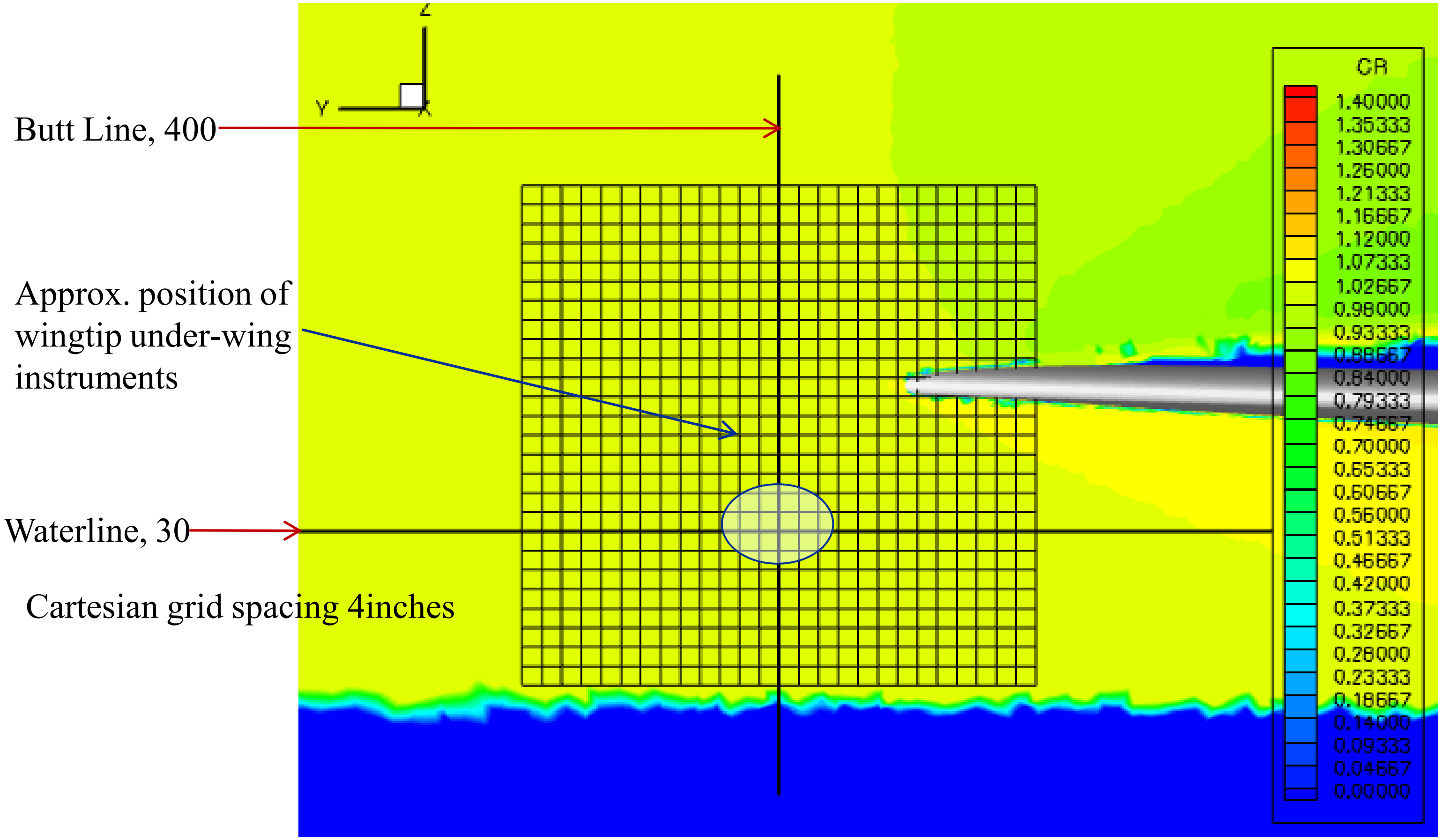
Particle Size, 100 μm; Axial Station, 512 inches



Particle Concentration Ratio Contours for wing tip mounted instruments

Tropical Day; AOAA, 5º; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Axial Station, 512 inches

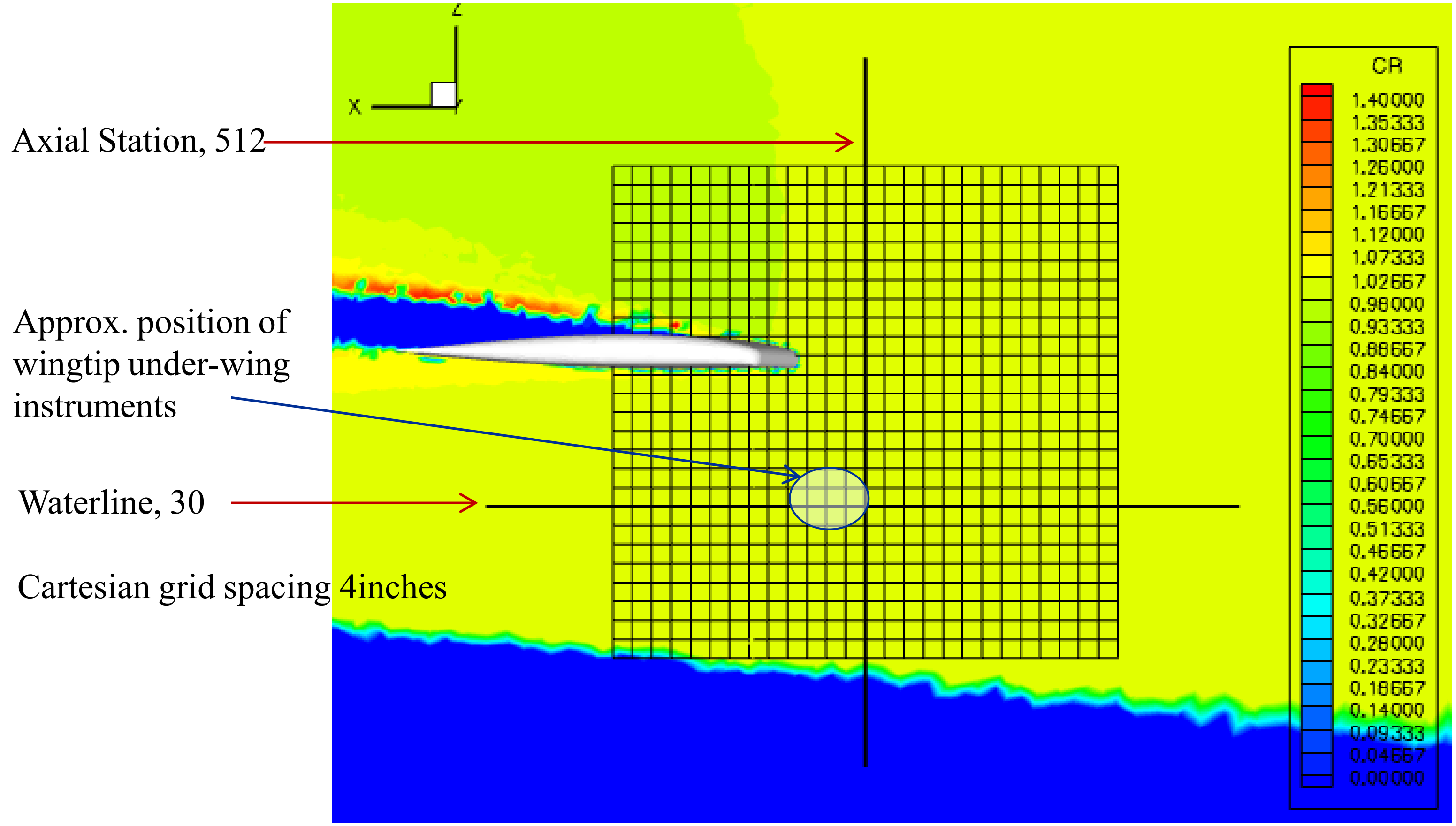


- Uniform concentration at proposed instrumentation location

Particle Concentration Ratio Contours for wing tip mounted instruments

Tropical Day; AOAA, 5º; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Butt Line, 400 inches

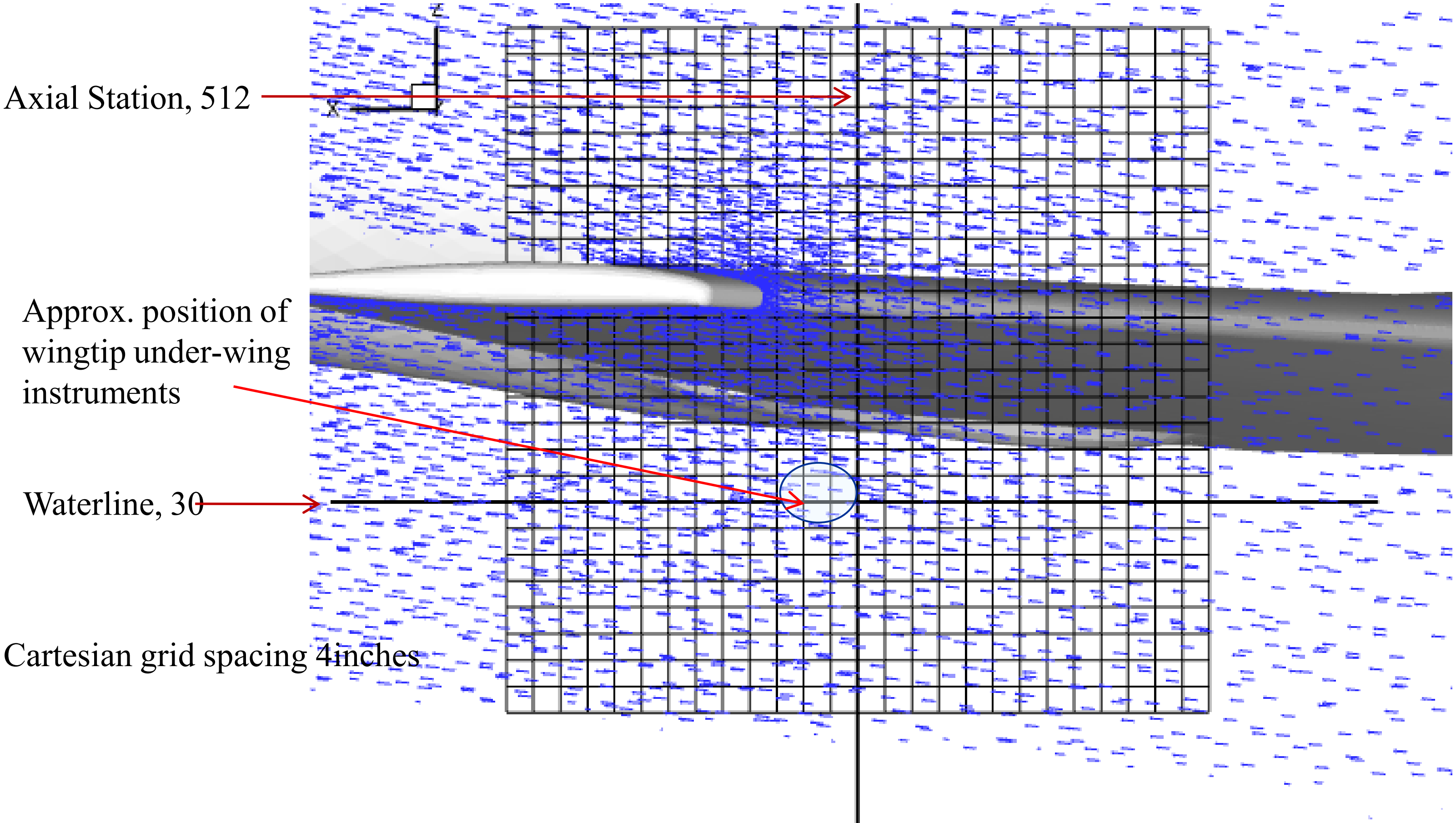


- Uniform concentration at proposed instrumentation location

Particle Velocity Vectors for wing tip mounted instruments

Tropical Day; AOAA, 5°; M, .74; Altitude, 40000 ft

Particle Size, 100 μm; Butt Line, 400 inches

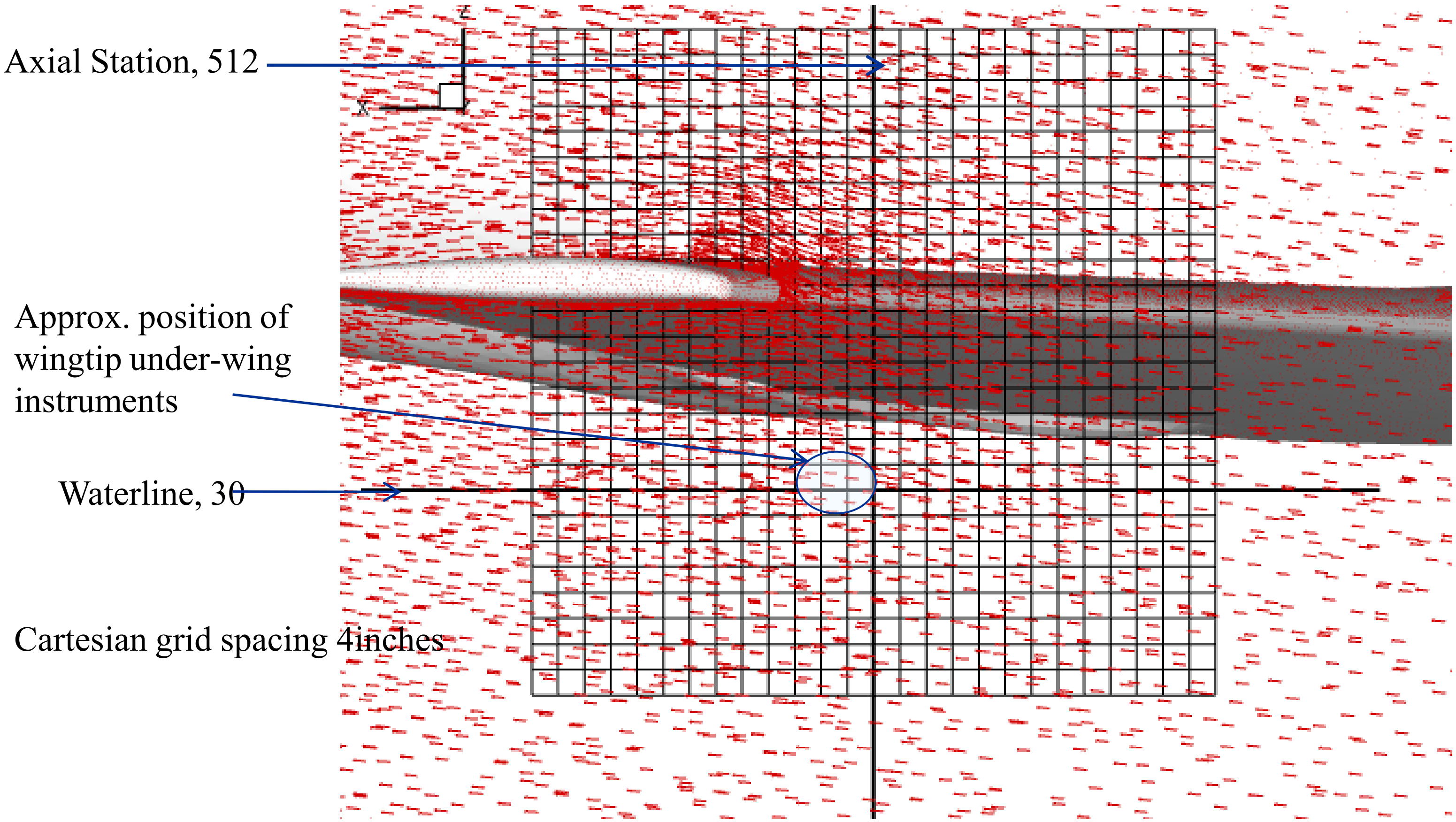


- Particle velocity vectors uniform at proposed instrumentation location

Air Velocity Vectors for wing tip mounted instruments

Tropical Day; AOAA, 5º; M, .74; Altitude, 40000 ft

Butt Line, 400 inches

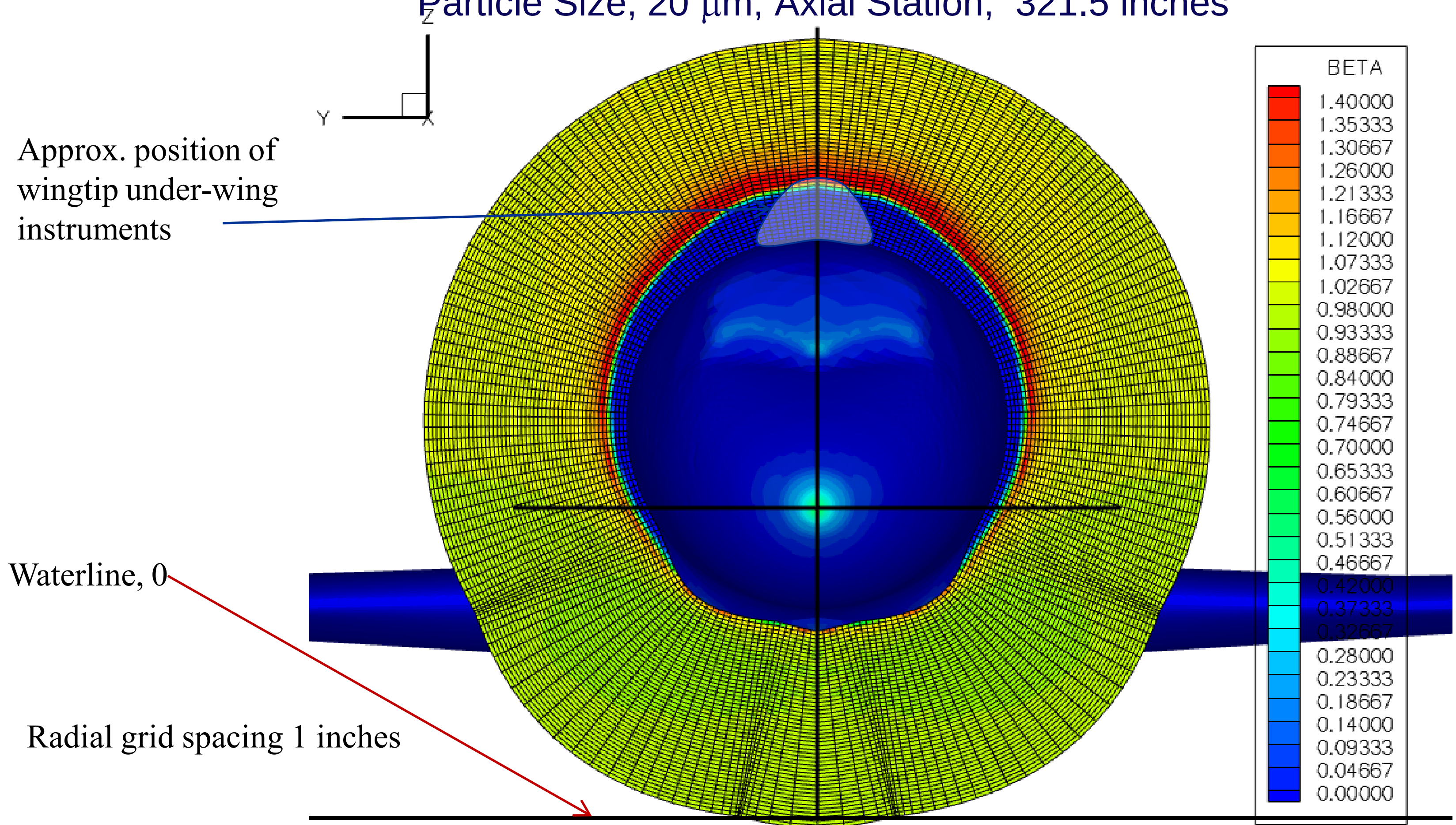


- Air velocity vectors uniform at proposed instrumentation location

Particle Concentration Contours at proposed roof mounted radar radome site

Tropical Day; AOAA, 5º; M, .74; Altitude, 40000 ft

Particle Size, 20 µm; Axial Station, 321.5 inches



- Shadow zone on top fuselage is 12 inches
- Radome surfaces that extend more than 12 inches above surface will collect ice in supercooled liquid conditions.

Conclusions

- Fuselage mounted instruments
  - Locations between station 57-80 inch provide similar particle concentrations (greater than unity due to particle bounce) about the radial positions.
  - No shadow zones identified near surface for station 57-80

- Inboard under-wing pylon mounted instruments
  - Locations Station: 270”, Waterline: +30”, Butt Line: +-51” provide uniform particle concentration (representative of free stream condition)
    - Inboard probes on these pylons may have some effect due to particle bounce, however it’s unlikely due to energy loss in particle bounce and due to particle breakup
  - Extinction probe beam may intercept some ice particle bounce debris under the fuselage
    - Depends on how much energy loss in particle bounce and break up.

Conclusions

- Wing-tip under-wing pylon mounted instruments
  – Locations Station: 512”, Waterline: +30”, Butt Line: +-400” provide uniform particle concentration (representative of free stream condition)

- Upper fuselage radar radome position
  – Location at station 321 inch on top of fuselage skin has a 12” shadow zone for proposed flight conditions
  – Radome surfaces that extend above 12” from surface will accrete ice in supercooled liquid conditions
  – More analysis is necessary once radome shape is defined to predict the location and mass of ice buildup on the radome